

Progress towards a universal family of UV-IR extinction laws

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Abstract

We present our progress on the study of extinction laws along three different lines. [a] We compare how well different families of extinction laws fit existing photometric data for Galactic sightlines and we find that the Maíz Apellániz et al. (2014) family provides better results than those of Cardelli et al. (1989) or Fitzpatrick (1999). [b] We describe the HST/STIS spectrophotometry in the 1700-10 200 Å range that we are obtaining for several tens of sightlines in 30 Doradus with the purpose of deriving an improved wavelength-detailed family of extinction laws. [c] We present the study we are conducting on the behavior of the extinction law in the infrared by combining 2MASS and WISE photometry with Spitzer and ISO spectrophotometry.

1 Don't we know everything about extinction laws already?

The answer to that question is no, not really. Here are some of the pending issues regarding extinction laws:

- In the mid-infrared (MIR): how do the water, aliphates, and silicates features vary among sightlines?
- In the near-infrared (NIR): what is the slope of the power law that is commonly used to characterize the extinction law? Is it universal?

- In the optical range: what is the functional form of the extinction law? How do you include the diffuse interstellar bands (DIBs)? Can we find sightlines to measure the extinction law from 3000 Å to 30 μm continuously?
- Are the IR/optical and the ultraviolet (UV) extinction laws correlated or not?

Some of the problems above are related to the lack of data e.g. very few UV sightlines have been measured at low metallicity. Others are due to the existence of published works with calibration issues or with outdated methods. Once we solve those questions we can attack with confidence more profound ones such as how the extinction law varies as a function of the type of environment. Considering that extinction affects a large number of astronomical measurements, it is important we understand how to correct for it.

2 What are we doing about it?

Here we describe our work on the field of extinction. We have already published the following:

- A new family of optical/NIR extinction laws (Maíz Apellániz et al. 2014a) based on modern 30 Doradus data.
- New UV sightlines in the SMC that are different from previous ones (Maíz Apellániz & Rubio 2012).
- A preliminary analysis of the IR extinction (Maíz Apellániz 2015a).
- The relationship between the optical DIBs and extinction (Maíz Apellániz et al. 2014b, Maíz Apellániz 2015b).
- Studies of specific sightlines (Arias et al. 2006, Maíz Apellániz et al. 2015a, 2015b, 2015c).
- Different calibration issues (Maíz Apellániz 2004, 2005a, 2006, 2007, 2013a, 2013b).

We currently have three different open lines and in this contribution we discuss their status. They are:

- Comparing different families of extinction laws in the Galaxy.
- STIS 1700-10 200 Å spectrophotometry of 30 Doradus OB stars.
- A study of the IR extinction with photometry and spectrophotometry.

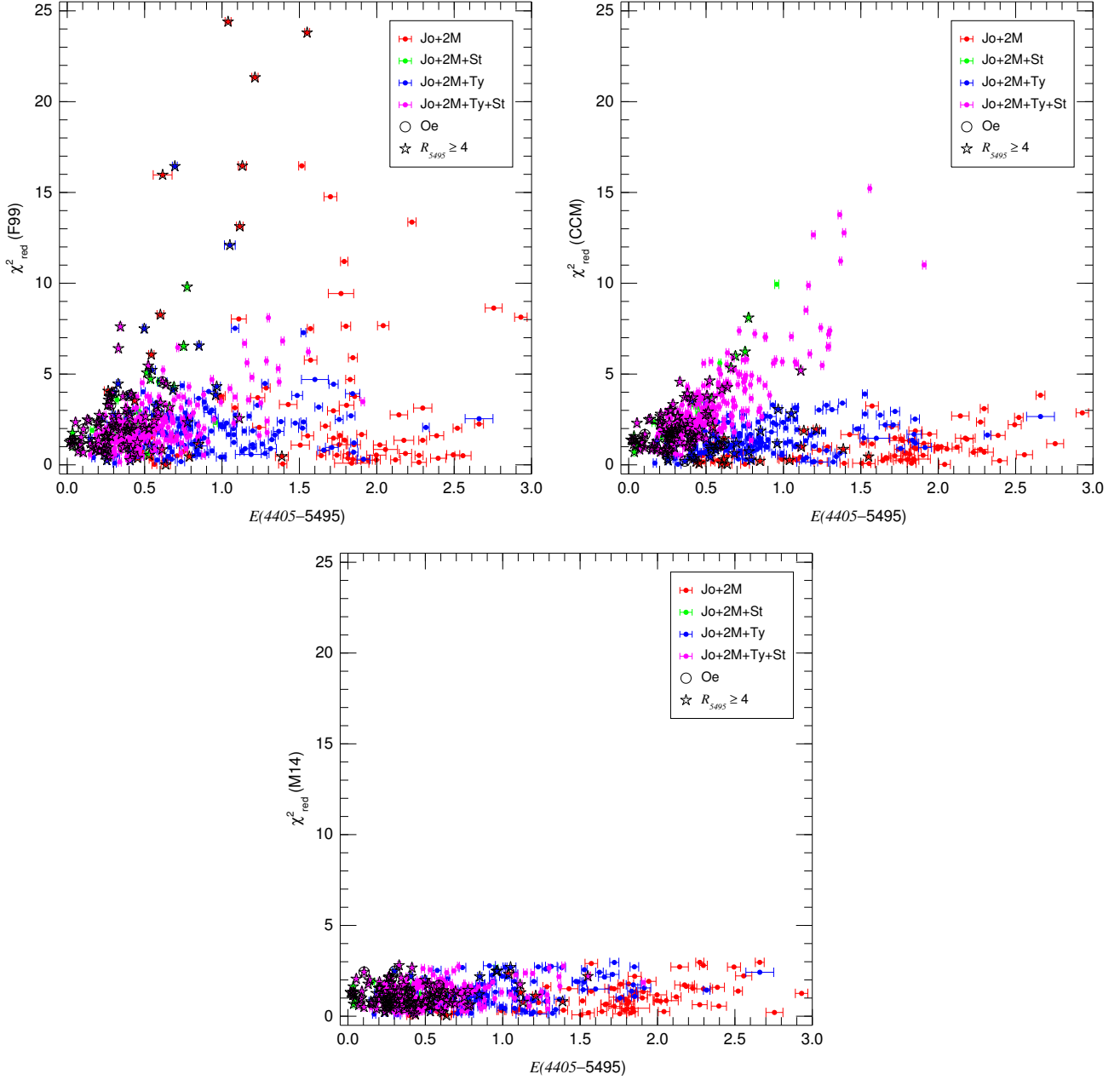


Figure 1: Reduced χ^2 of the CHORIZOS fit to the photometry of the GOSSS I+II+III sample as a function of the amount of extinction $E(4405 - 5495)$. The top left, top right, and bottom panels are for the F99, CCM, and M14 families of extinction laws, respectively. Different colors are used to indicate the photometric bands available for each star (Jo = Johnson *UBV*, 2M = 2MASS *JHK_s*, Ty = Tycho-2 *BV*, St = Strömgren *uvby*). Additional symbols are overplotted for Oe stars and objects with large values of R_{5495} (i.e. extinction caused by large grain sizes).

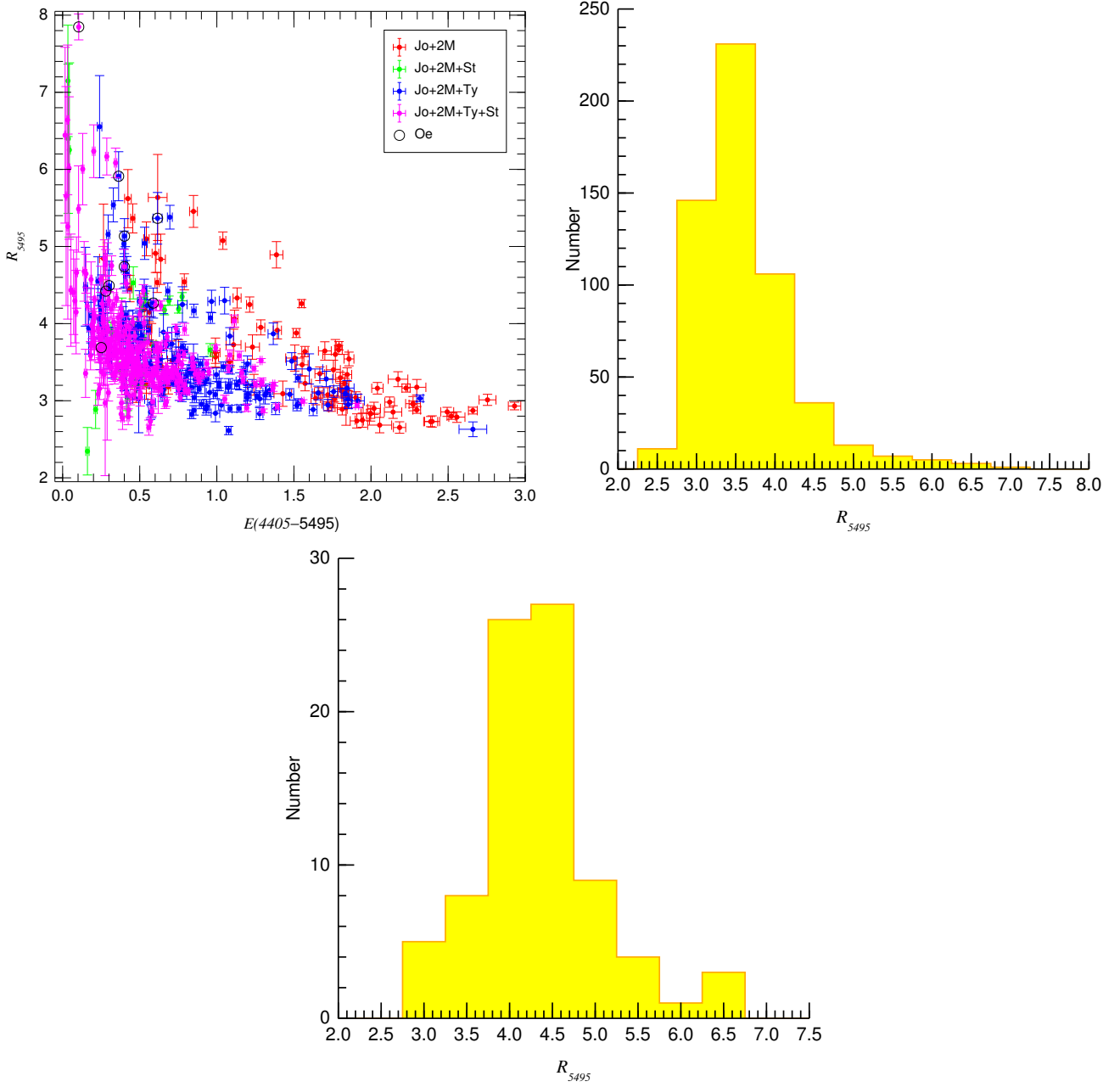


Figure 2: [top left] R_{5495} as a function of $E(4405 - 5495)$ for the CHORIZOS fits for the GOSSS I+II+III sample using the M14 family of extinction laws. See Fig. 1 for the symbol nomenclature. [top right] R_{5495} histogram for the Galactic GOSSS I+II+III sample. [bottom] R_{5495} histogram for the 30 Doradus VFTS sample of Maíz Apellániz et al. (2014a).

3 Comparing extinction-law families

Data. We have collected optical-NIR photometry for the GOSSS I+II+III sample (Sota et al. 2011, 2014, Maíz Apellániz et al. 2016). All targets have Johnson *UBV* and 2MASS *JHK_s*, some have Tycho-2 *BV* and/or Strömgren *uvby*.

What have we done? We fit the amount $[E(4405 - 5495)]$ and type $[R_{5495}]$ of extinction for each star using CHORIZOS (Maíz Apellániz 2004, 2013b) and three families of extinction laws: F99 (Fitzpatrick 1999), CCM (Cardelli et al. 1989) and M14 (Maíz Apellániz et al. 2014a). See Fig 1.

Results. We first study which family provides better fits to the data.

- F99: poorest fits of all three families, especially for large values of R_{5495} .
- CCM: overall better than F99 except for targets with Strömgren photometry due to its use of a seventh-degree polynomial in $1/\lambda$ for interpolation in the optical.
- M14: best fits of all, with a reduced χ^2 always under 3.0.

We point out that even though the M14 family was derived using 30 Doradus data, it provides a better description of Galactic optical-NIR extinction than either the F99 or CCM families.

Once we have determined that the M14 family provides the best results of the three, we show in Fig. 2 some of the results found for $E(4405 - 5495)$ and R_{5495} .

- As previously known, the majority of Galactic sightlines have R_{5495} between 3.0 and 3.5.
- At very low extinctions $[E(4405 - 5495) < 0.2]$ the error bars on R_{5495} are too large to yield significant results.
- There are few stars with $R_{5495} < 3.0$ (sightlines with many small dust grains) but they are dominant among objects with large extinction.
- In the range $0.2 < E(4405 - 5495) < 1.2$ there is a significant fraction of stars with large values of R_{5495} . Those sightlines are depleted in small grains and are associated with H II regions.
- The R_{5495} histograms for the Galaxy and 30 Doradus are markedly different, with the latter showing a larger fraction of high- R_{5495} sightlines. The differences can be explained by [a] the lower values of $E(4405 - 5495)$ and [b] the larger fraction of H II region sightlines in 30 Doradus.

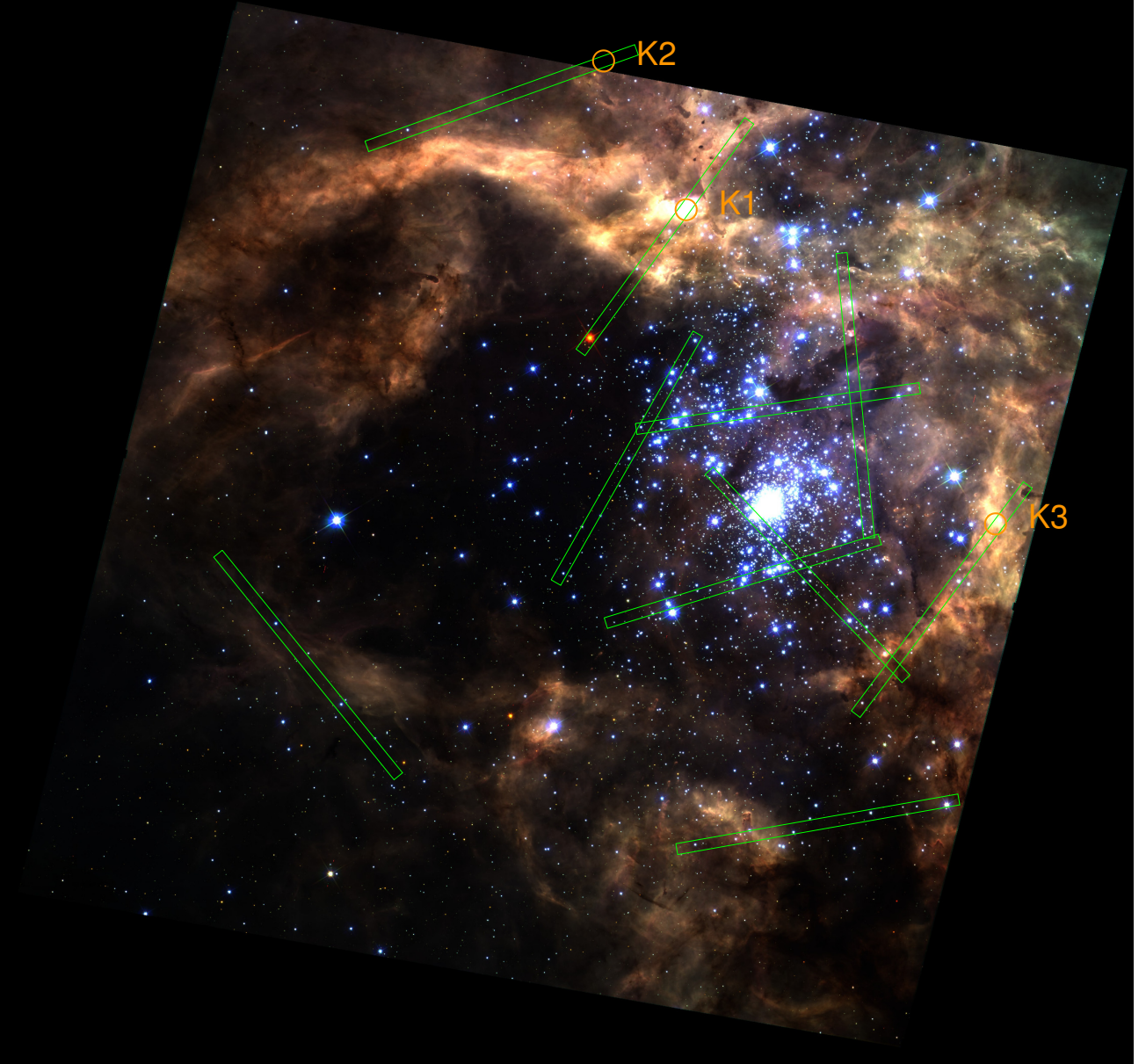


Figure 3: UVIS-WFC3 image of 30 Doradus with the ten STIS slits overimposed. The slit locations and PAs were selected to include a large variety of values of R_{5495} and of environments, from stellar cocoons to the diffuse ISM. Knots 1, 2, and 3 from Walborn et al. (2002) are marked. The field size is $206'' \times 194''$, N is top, and E is left.

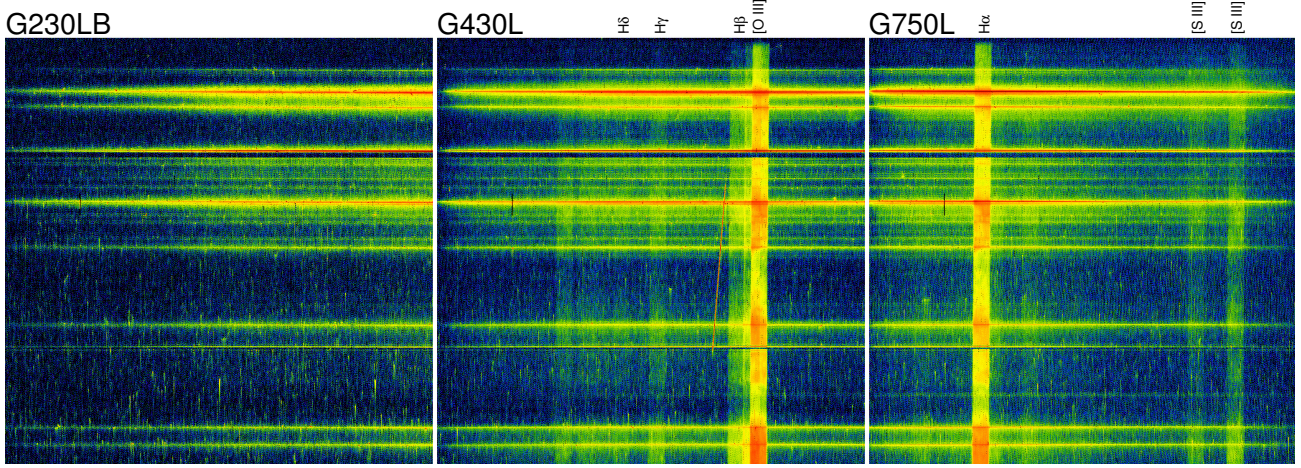


Figure 4: G230LB+G430L+G750L (1700-10 200 Å) STIS exposures of one of the ten 30 Doradus slits. The horizontal coordinate is wavelength and the vertical one is slit position (covering 51''). This slit covers a region close to R136 which is relatively dense in OB stars and has an intermediate nebular intensity. The positions of some prominent nebular lines are marked. Note that since we are using a 2''-wide slit, each nebular line creates a rectangular image in the CCD. The two horizontal dark regions are caused by occulting bars.

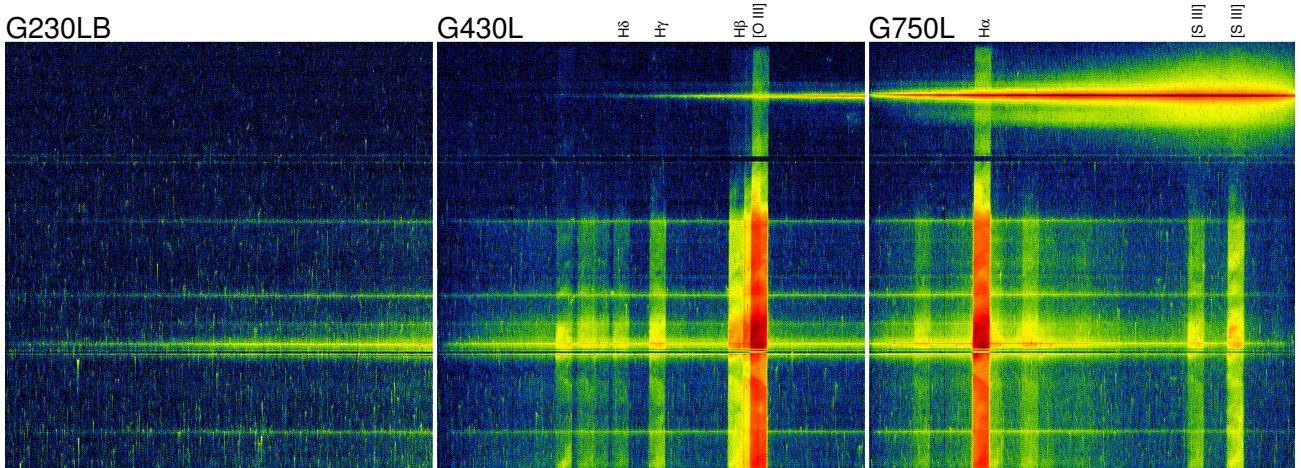


Figure 5: Same as Fig. 4 but for a different slit. The lower half has several OB stars immersed in intense nebulosity while the upper half is dominated by a red supergiant in a region with little nebulosity.

4 30 Doradus with STIS

We are obtaining 10 visits of HST/STIS spectrophotometry under GO program 14104 (9 of them have been executed as of October 2016, Fig. 3). For each visit we use three gratings, G230LB+G430L+G750L, in order to continuously cover the 1700-10200 Å range. We use the 2"-wide slit in order to obtain data for 30 OB stars (Figs. 4 and 5). The stellar spectra are extracted with MULTISPEC (Maíz Apellániz 2005b) to correctly eliminate nebular contamination. The stars were selected to probe different environments: H II region, diffuse ISM, and molecular gas. The questions we want to answer are:

- What are the UV-NIR detailed (~ 100 Å resolution) extinction laws?
- Is the Whitford (1958) knee real and does it exist for all values of R_{5495} ?
- Are there real differences between the Galactic and 30 Doradus UV extinction laws?

5 Infrared extinction

We aim to derive a detailed IR extinction law for OB stars in the solar neighborhood; tie it up with the optical extinction law finding appropriate sightlines; and analyze possible variations, checking if there is a relationship with R_{5495} . Our strategy is:

- Collect Spitzer+ISO spectrophotometry and Spitzer photometry for GOSSS stars.
- Collect and reprocess WISE photometry.
- Use WISE imaging to determine the type of environment.
- Combine the data to fit: [a] atmosphere SED, [b] wind, and [c] extinction law for each sightline (Fig. 6).

In the process of measuring the MIR extinction law, we collected and reprocessed the WISE photometry for the GOSSS I+II+III sample. We tested the validity of the W1+W2+W3+W4 photometry comparing the results from the All-Sky (Cutri et al. 2012) and AllWISE (Cutri et al. 2013) data releases. We compared the PSF photometry from the data releases with new aperture photometry using a realistic sky evaluation. We also derived saturation corrections and identified cases with large uncertainties. We will use our results to study the relationship between extinction and the environment.

- WISE W3+W4 can be used to identify the presence of the warm dust associated with H II regions, detecting them even at high extinctions.
- We morphologically classified the sample using the WISE images (Fig. 7) in order to study possible variations in the extinction law.

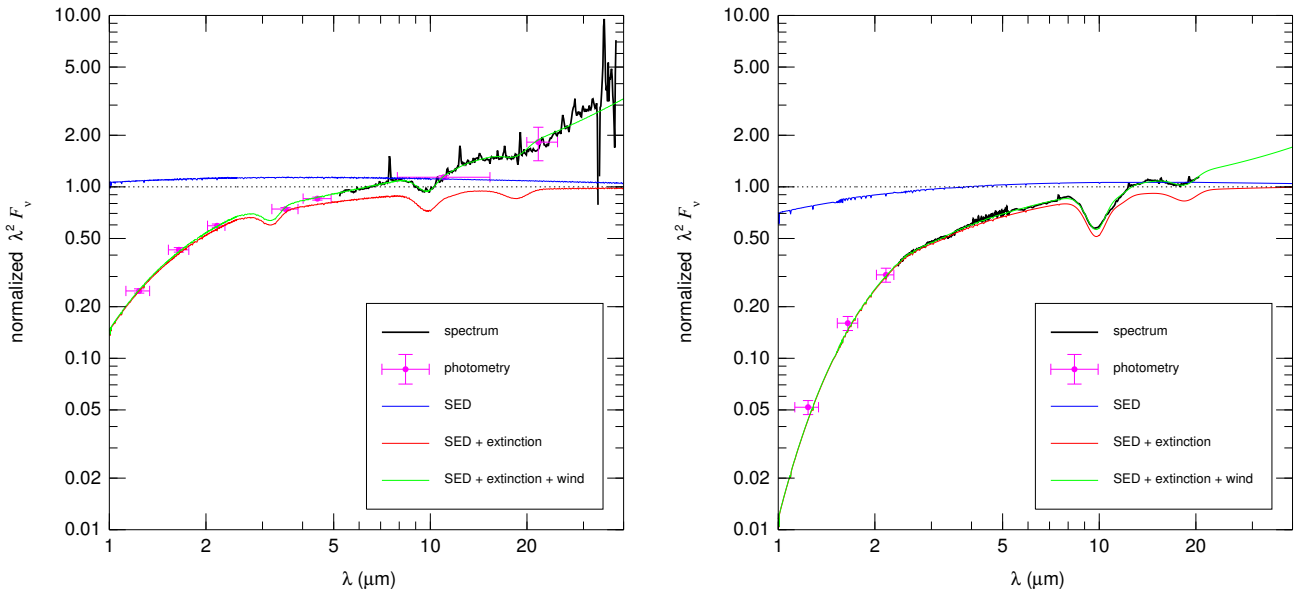


Figure 6: Two examples of atmosphere SED + wind + extinction law fits. [left] An O star with moderate extinction and strong wind with 2MASS JHK_s and WISE W1+W2+W3+W4 photometry and Spitzer spectrophotometry. [right] A B star with high extinction and moderate wind with 2MASS JHK_s photometry and ISO spectrophotometry. The vertical scale is $\lambda^2 F_\nu$ normalized to the atmosphere SED value at infinity.

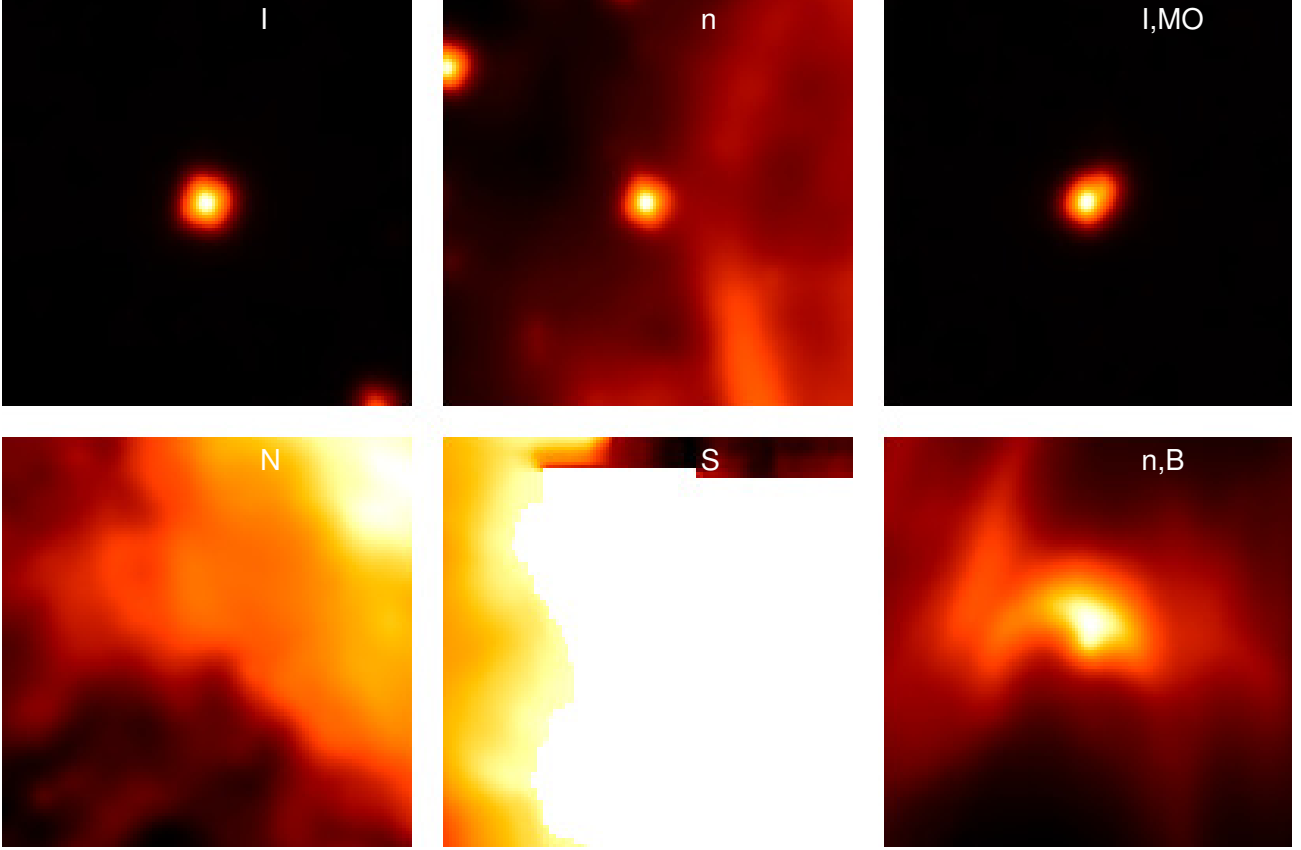


Figure 7: WISE W3 images and morphological classifications for six GOSSS I+II+III stars. Each field is $3' \times 3'$, with N towards the top and E towards the left, the target at the center, and a logarithmic intensity scale.

- We use the following main flags: I (isolated), n (weak nebulosity), N (strong nebulosity), S (saturated background i.e. bright H II region).
- We use the following optional flags: MO (hidden multiplicity in WISE, optical companion), MI (hidden multiplicity in WISE, IR companion), B (bow shock visible).

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